



Measurement Variability of Vertical Scanning Interferometry Tool Used for Orbiter Window Defect Assessment

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Abstract

The ability to sufficiently measure orbiter window defects to allow for window recertification has been an ongoing challenge for the orbiter vehicle program. The recent Columbia accident has forced even tighter constraints on the criteria that must be met in order to recertify windows for flight. As a result, new techniques are being investigated to improve the reliability, accuracy and resolution of the defect detection process. The methodology devised in this work, which is based on the utilization of a vertical scanning interferometric (VSI) tool, shows great promise for meeting the ever increasing requirements for defect detection. This methodology has the potential of a 10-100 fold greater resolution of the true defect depth than can be obtained from the currently employed micrometer based methodology. An added benefit is that it also produces a digital elevation map of the defect, thereby providing information about the defect morphology which can be utilized to ascertain the type of debris that induced the damage. However, in order to successfully implement such a tool, a greater understanding of the resolution capability and measurement repeatability must be obtained. This work focused on assessing the variability of the VSI-based measurement methodology and revealed that the VSI measurement tool was more repeatable and more precise than the current micrometer based approach, even in situations where operator variation could affect the measurement. The analysis also showed that the VSI technique was relatively insensitive to the hardware and software settings employed, making the technique extremely robust and desirable.

1.0 Introduction

As a result of the Columbia accident, a number of safety related concerns have emerged in the orbiter vehicle program. One such concern centers around the ability/capability to adequately locate and measure orbiter window defects which accumulate from several type of debris sources [1] during shuttle missions. Of particular interest is the ability to accurately and precisely determine defect depth, as this parameter dictates whether or not a window needs to be taken out of service [2]. The current methodology for defect assessment utilizes an “optical-micrometer” tool wherein a replica of the defect is sectioned and viewed on end such that the section profile can be interrogated to ascertain the maximum depth. This process relies heavily on the limited depth of field of the objective lens to locate the profile peak, at which point the operator measures the distance from the base of the section to the planar located peak using an integrated micrometer based measurement tool. This measurement technique has been shown to have an accuracy of about 0.0002 inches ($\sim 5 \mu\text{m}$) with a variability of about the same magnitude [3] (Note: because of past practices and for convenience all subsequent measurements will be reported in “mils”, where 0.0002 inches = 0.2 mils). However, the current specification for window certification requires assessment of defects as small as 0.6 mils and calls out for the measurement technique to

be capable of a factor of 10 greater measurement resolution. Given these constraints, the current process marginally meets the measurement need but doesn't have the required precision for the specification called out in the certification process. An alternate method based on vertical scanning interferometry (VSI) was proposed as this technique has the ability, under ideal conditions, to measure and reconstruct surface morphologies with vertical resolutions down to ~ 0.00039 mils ($0.01\ \mu\text{m}$) [4]. These surface morphologies can be interrogated for a host of different parameters including, but not limited to, maximum defect depth. The purpose of this study, therefore, was to prove the feasibility of utilizing the VSI technique to provide accurate depth measurements and to quantify the measurement variability that could be expected from using a VSI based inspection methodology for measuring surface defects. This, then, would provide justification for the orbiter window program to pursue a more rigorous procedures definition and measurement reliability certification effort. Once certified, by showing acceptable results in a double blind, multivariable assessment, the tool would then be utilized to determine go/no-go criteria for all windows needing flight worthiness recertification.

2.0 Vertical Scanning Interferometry (VSI)

Vertical Scanning Interferometry (VSI), commonly referred to as white light interferometry or optical profilometry, is a process of accurately reconstructing the morphology of a sample surface by scanning a specially designed objective lens towards the sample of interest and observing the fringe modulation which occurs as a result of this process. Accurate morphological information is determined as follows. First, light from a high intensity light source is sent through a beam splitter (See Figures 1 and 2 for details on how the system works). Half of the light emanating from the beam splitter is sent to a reference path. The other half of the light emanating from the beam splitter is sent through the modified objective lens (commonly referred to as a Mirau Interferometer), impinges on the sample surface and is recollected by the objective. Both signals are then recombined for processing by the sensor. The system is constructed such that when an area of the sample surface is at the focal plane of the objective lens, the reference path length will be identical to the imaged path length. At working distances close to the focal plane of the objective, interference fringes will develop as a result of the recombining of the two signals. By monitoring the intensity of the fringe modulation and determining when the fringe modulation intensity is maximized, it is possible to determine when the objective lens is at the point of maximum focus. Thus, as the objective lens is scanned toward the sample, each pixel on the CCD array is monitored for fringe modulation intensity as a function of objective vertical position. Subsequent to the scan, the modulated intensity signal for each pixel is interrogated to determine the maximum modulation at which point the pixel is assigned a vertical position corresponding to the position of the objective when the maximum modulation occurred. At this point, the X-Y-Z coordinate for each pixel in the field of view can be determined and a 3-D reconstruction of the surface morphology can be constructed.

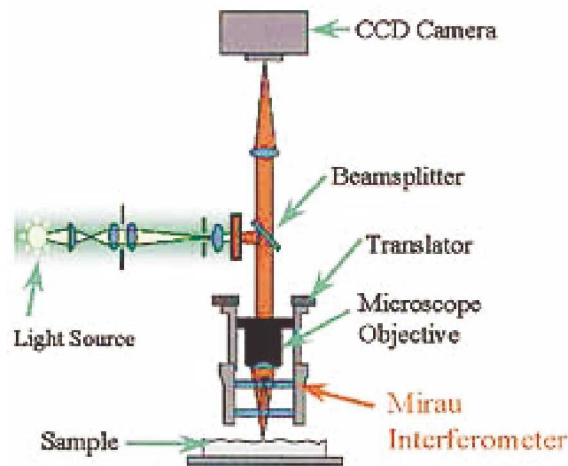


Figure 1: Schematic of a vertical scanning interferometer depicting how the modulated signal is produced.

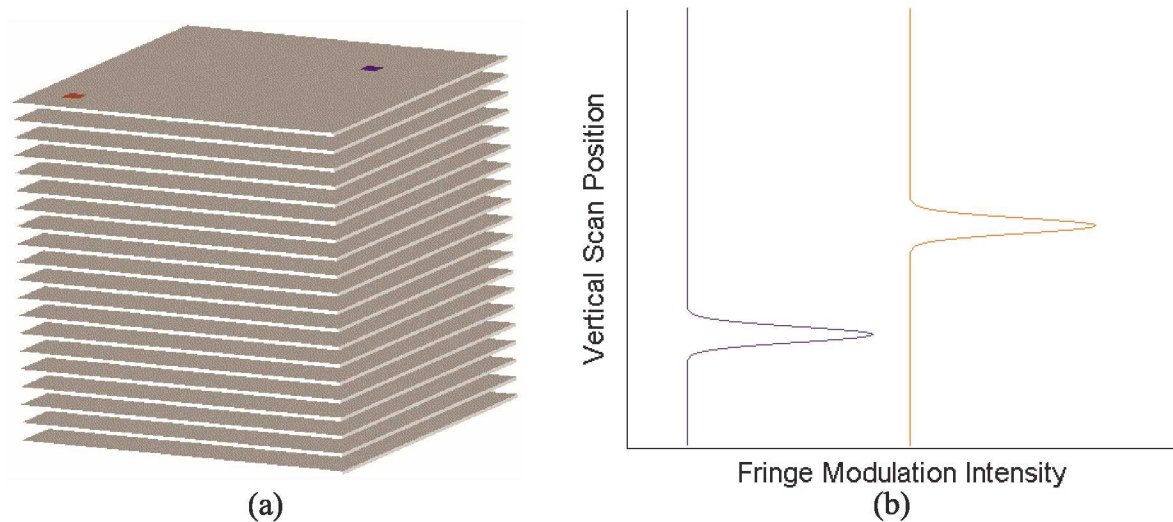


Figure 2: Example of the process for constructing 3-D surface through monitoring fringe modulation intensity. Each pixel of the sensor is monitored independently as the objective lens is scanned in the vertical direction, as shown in (a). After the scan has completed, the fringe modulation intensity profile for each pixel is interrogated for the point of maximum modulated intensity and the corresponding vertical scan position for this condition is established to construct the X-Y-Z coordinate information for the surface, as shown in (b) for two of the pixels in (a).

Although the vertical resolution of this technique is not limited by the depth of field of the objective lens used, the surface height measurement will be somewhat dependent on the magnification

used to perform the scan. This dependence comes about as a result of the fixed imager which is used to collect the reflected signal. Since the size of the imager is fixed, the effective magnification of the scan will dictate the horizontal resolution of the scan which in turn dictates the accuracy of the height measurement. However, as will be seen in the measurements to follow, this dependency of the measured height on effective magnification had only a limited effect on the defect depth measurement at the levels of interest herein.

In order to determine the viability of utilizing the VSI based technique to assess defect depths, a number of different measurements were made both on real, uncoated orbiter window replicas and directly on glass defect standards of known depth. These measurement scenarios are outlined in the following sections. For the purposes of the work conducted herein, measurements were examined in three different ways. First, the overall spread in the measurements was assessed to obtain a better understanding of how large a variation was possible. Second, the “accuracy” of the measurement was assessed by comparing the mean of the VSI measurements to the mean of the measurements taken from the currently employed micrometer based inspection tool. It is important to note, however, that this statistic could be incorrect because of the sensitivity capability of the micrometer based technique. Thus, although the measurement made with the micrometer based technique is assumed to be accurate, it may very well not be, thereby causing the VSI accuracy to be viewed incorrectly. Thus, less weight was placed on this particular statistic for the purposes of this analysis. Finally, the “precision” of the measurements was defined by taking the standard deviation of the measurements made using the VSI approach. This statistic then defines how well grouped the measurements were even if the measurements themselves differed slightly from the “true” value as defined by the currently employed micrometer based technique.

3.0 Procedures and Results

A number of different measurements were taken in order to ascertain the reproducibility of the interferometry based tool. The potential sources of error in each of these measurements were investigated to determine the effect each had on the reproducibility of the measurement. The following sections outline the results of those findings.

3.1 Uncoated Orbiter Window Replica Measurements

The current windows inspection process utilizes a replica in order to determine defect depth. In general, a system whereby the defect depth could be measured directly on windows mounted on the vehicle would be desired. Until such times, replica usage will remain the predominant mode of measurement but improvements in the way in which the depth measurements are made from these replicas must be obtained due to the ever increasing detection requirements. To this end, a detailed look at the variability of measurements made with the newly developed interferometry based technique (See Figure 3) were assessed in order to understand which variables produced the greatest sources of error for the measurement and at what level these errors affected the outcome.

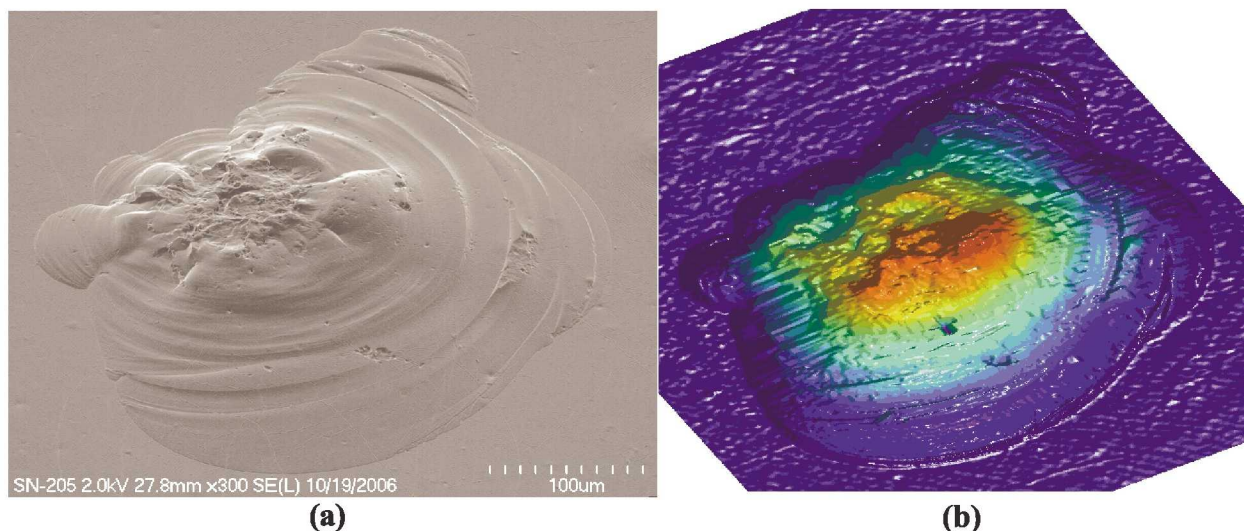


Figure 3: (a) Scanning electron micrograph (SEM) and (b) low magnification, vertical scanning interferometry (VSI) reconstruction of an orbiter-window replica. Note that the defect size and depth information is captured as a digital elevation map (DEM) and can be presented as an overlaid color map for easier interpretation.

The first variable that was interrogated was the scan-to-scan variation of the same defect under identical scan settings. This variation results from subtle differences in the way light impinging on the replica surface refracts and is recollected to produce the surface measurement. Since the surface is not a perfect reflector, differences can occur in the way in which light is scattered thereby affecting the measurement. In order to assess the reproducibility of the VSI technique, a set of scans were performed at low magnification. Prior to performing the scans, the operator searched the sample surface at low magnification to locate the defect of interest, as would be done in practice. Once the defect was located, the operator initiated the scan using appropriate intensity, scan length and magnification settings. In this case, scans were performed on the same replica with no adjustment of either the sample position or scan parameters between successive scans. Table 3.1-1 shows the result of performing this operation, on three successive scans, using a 20X objective lens with a 1X Field Of View (FOV) lens. This setup produced an effective magnification of ~20X (the product of the objective lens magnification and the FOV magnification).

Table 3.1-1: Repeat Measurements of Single Defect Using Identical Instrument Settings

| Measurement Type | Scan 1 | | Scan 2 | | Scan 3 | |
|----------------------|--------|-------------------|--------|-------------------|--------|-------------------|
| | (mils) | (μm) | (mils) | (μm) | (mils) | (μm) |
| Maximum Defect Depth | 1.113 | 28.270 | 1.119 | 28.423 | 1.117 | 28.372 |

As can be seen from the results in Table 3.1-1, the scan-to-scan variation on the peak measurement resulted in a range of values differing by 0.006 mils (0.152 μm) which correlates to a range

of ± 0.003 mils ($\pm 0.076 \mu\text{m}$). This same defect was determined to have a depth of 1.16 mils ± 0.20 mils ($29.46 \mu\text{m} \pm 5 \mu\text{m}$) by the currently employed micrometer-based measurement technique. This result deviates from the average measurement made via the interferometry technique by 3.91%.

Next, operator-to-operator variations were assessed in conjunction with setup conditions to measure an entirely different defect. Each operator was required to locate the defect at an effective magnification of $\sim 20\times$, choose appropriate parameters and lighting intensity for the scan and subsequently perform the measurement. Table 3.1-2 lists the results of this process. Note here that measurements were taken on both vertical and horizontal profile sections and that the level of reproducibility from operator-to-operator on a single scan showed less deviation than was seen for the scan-to-scan variation.

Table 3.1-2: Operator-to-Operator Variation on Critical Size Flaw/Defect

| Measurement Type | Operator 1 | | Operator 2 | |
|--|------------|-------------------|------------|-------------------|
| | (mils) | (μm) | (mils) | (μm) |
| Maximum Defect Depth (Measured from Horizontal Section) | 0.690 | 17.526 | 0.693 | 17.602 |
| Maximum Defect Depth (Measured from Vertical Section) | 0.740 | 18.796 | 0.738 | 18.745 |

Although the operator-to-operator measurement range was 0.003 mils ($0.076 \mu\text{m}$), the peak measurement was observed to vary by as much as 0.05 mils ($1.27 \mu\text{m}$), depending on whether a vertical or horizontal section was used to make the measurement. Although this variation was below the current requirement for sensitivity (which currently is 0.06 mils ($1.52 \mu\text{m}$)), it introduces an order of magnitude shift in the sensitivity capability of the instrument, as compared to the measurements reported in Table 3.3-1. The reason for this observed variation is not clear since both the vertical and horizontal measurements should be interrogating the same pixel information at the peak. Thus, further investigation along this front is warranted as this could pose a significant source of error.

The final experiment was performed to determine the effect of choosing drastically different operating conditions on the outcome of the measurement. Since operator influence does come into play with the interferometry based technique, some discretion is inherent to the process. In some cases, defect sizes will inevitably be borderline, with two different operators choosing to utilize a different combination of Objective Lens and Field of View (FOV) magnifications to perform the scan. As such, the variation that can result from such a decision should be quantified. It is important to remember that the combination of the Objective Lens magnification and the Field of View magnification combine to produce an Effective Magnification for the scan.

Table 3.1-3: Effect of Operator Choosing Different Effective Magnifications on Outcome of Measurement

| Measurement Type | 10X Magnification | | 20X Magnification | | 40X Magnification (noise in scan) | | 40X Magnification | |
|---|-------------------|-------------------|-------------------|-------------------|-----------------------------------|-------------------|-------------------|-------------------|
| | (mils) | (μm) | (mils) | (μm) | (mils) | (μm) | (mils) | (μm) |
| Maximum Defect Depth (Measured from Horizontal Section) | 0.797 | 20.24 | 0.782 | 19.86 | 0.789 | 20.04 | 0.783 | 19.89 |
| Maximum Defect Depth (Measured from Vertical Section) | 0.791 | 20.09 | 0.788 | 20.01 | 0.820 | 20.83 | 0.799 | 20.29 |

As can be seen from the results presented in Table 3.1-3, the variability incurred due to operator choice of objective and FOV combinations had only a very small affect on the reproducibility of the measurement. In one case (that of the 40X effective magnification with noise in the scan), the light intensity was set incorrectly and some noise appeared in the result. This noise was obvious to the operator who automatically looked to perform an alternate scan, the results of which are presented in the last column of Table 3.1-3. However, the results of the scan containing noise were presented to show that the level of error obtained even when parameters are blatantly wrong are negligible. Disregarding this scan with obvious problems, the variation from arbitrary selection of lens combinations yielded a spread of 0.017 mils (0.432 μm) with a precision on the order of $std\ dev = \pm 0.007$ mils (± 0.178 μm). This takes into account the variation when both horizontal and vertical section measurements are combined into one data set. If separated and analyzed independently, the error in the measurement changes to ± 0.008 mils (± 0.203 μm) and ± 0.006 mils (± 0.152 μm) for the horizontal and vertical sections, respectively.

3.2 Direct Measurement on Glass Standards

Three separate defects (1 hemispherical and 2 elongated scratches) were measured using the interferometer technique by performing scans directly on three known glass standards, believed to be NIST (National Institute of Standards and Technology) traceable [3]. The rationale for doing so was to determine whether or not scans produced directly on glass were as accurate as those performed on a replica or whether diffuse scattering of the impinging light on a semi-transparent surface produced additional error. This information is extremely important given that the ideal measurement scenario would allow for direct measurement of window defects without having to take the window out of service and without having to produce defect replicas. The results of the scans are presented in Table 3.2-1.

Table 3.2-1: Standard Measurements Performed Directly on Glass

| Defect Shape | Interferometer Measurement Direction | Specified Depth of Standard | | Depth Measurement from VSI Interferometer | |
|-------------------|--------------------------------------|-----------------------------|-------------------|---|-------------------|
| | | (mils) | (μm) | (mils) | (μm) |
| Hemispherical | Across Width | 0.750 | 19.050 | 0.751 | 19.075 |
| Elongated Scratch | Across Width | 0.500 | 12.700 | 0.553 | 14.046 |
| Elongated Scratch | Along Length | 0.750 | 19.05 | 0.741 | 18.821 |

In general, the agreement between the depth specified for the standard and that determined by the VSI technique showed that measurements made directly on glass should be equally reliable to those made on defect replicas. In actuality, the scans made directly on the glass may be more accurate, a result which is not reflected in the data presented in Table 3.2-1. This is because of the difficulty incurred in the measurement of the standard defects. Since the defects were created via a mechanical process, the troughs of the defects showed an irregularity on the order of $\pm 1.5 \mu\text{m}$. As such, it was decided that as a first approximation, the operator would visually average the variation in the trough variability in order to set the baseline for the measurement. This process is depicted in Figure 4 for more insight. With this approach, the accuracy of the measurements made directly on glass were, in general, observed to be consistent with the accuracies for measurements taken on defect replicas, reported in the previous section. Of course, more thorough testing is still required to statistically validate this conclusion.

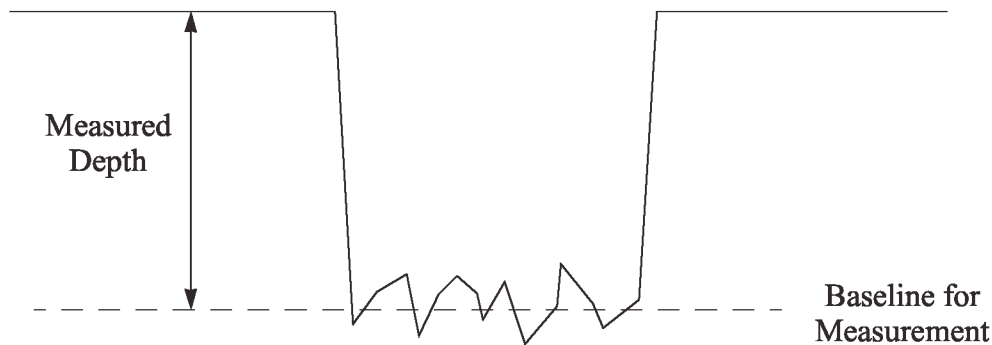


Figure 4: Methodology behind visually setting baseline for standard depth measurement due to irregular defect bottom.

The only exception to this was the measurement taken on the 0.5 mil deep scratch which was measured across the scratch rather than along it. This measurement showed a deviation of 0.053

mils (1.346 μm) from the indicated depth. However, qualitative inspection of height contours within the defect showed a wide variation in the uniformity of the depth along the scratch. It was for this reason that the third defect (a deeper elongated scratch) was measured along the length. By doing so, more of the depth variability was averaged into the positioning of the baseline for the measurement thereby producing a more accurate result.

Conclusions

The vertical scanning interferometry technique employed here was capable of accurately resolving the features of interest and should be adequate for the successful certification of shuttle windows for flight. The experiments performed in this work demonstrated that this measurement tool was more repeatable than the current micrometer based approach and showed more precise measurement capability even in situations where operator variation could affect the outcome/measurement. The measurements also showed that the VSI technique was relatively insensitive to the hardware and software settings employed, which yields a measurement operation which is extremely robust. However, in order for this tool to be implemented within the Orbiter program, a more detailed/rigorous statistics based assessment must be performed in order to validate/determine the true variability of the process. Finally, the results of this effort have shown that more work should be performed to determine the reason behind the variability incurred from ascertaining defect depth via a horizontal section versus a vertical section. Also, the systematic, step-by-step procedures should be further solidified for this measurement process in order to insure that any variation seen is the result of the statistical variation in the measurement and not related to procedural issues.

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